Breaking of Axial and Reflection Symmetries in Spontaneous Fission of Fermium Isotopes

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INTRODUCTION

Majority of nuclei in their ground states possess axially symmetric and reflection symmetric mass distributions. In course of a fission process a shape of the nucleus changes from weakly deformed in the ground state to an elongated one at the saddle point and to two, perhaps different, fragments at the scission point. In the process of fission the primary symmetries of the mass distribution usually break down in some points to some transitional non-axial and left-right asymmetric configurations. The former affects the saddle point while the latter modifies the final stage of the fission process.

The symmetries of the distributions at the scission points also depend on the nucleus and show different and heterogeneous patterns. Low level symmetries like the axiality and/or the reflection symmetry have very strong effects on the basic properties of nuclei. Fission barrier is an example. As the barrier is responsible for *e.g.*, fission half life, the latter is affected as well. The radical change of properties is a consequence of a release of axial symmetry to the triaxial one and/or similarly the release of the reflection symmetry to the reflection asymmetry of the mean field. The former leads to the decrease of the first fission barrier while the latter is responsible for the asymmetric fission just opening an additional fission channels in the reflection asymmetric part of a deformation space. This reveals a new phenomena and gives a possibility to study new processes like *e.g.*, bimodal [1] or multimodal fission.

The non-axial and reflection asymmetry are experimentally established facts and both have to be confirmed by any realistic model of the nucleus. In the following we study the effects of releasing strict axial symmetry and allowing the triaxiality of the nuclear shapes and we consider the reflection asymmetric configurations within the Hartree-Fock-Bogoliubov (HFB) theory and the Skyrme SkM* force [2].

Some of the effects mentioned were already reported elsewhere in early models of the nuclear fission like *e.g.*, a microscopic-macroscopic approach (see Refs. [3-7]) and in the of case more modern Hartree-Fock+BCS (HF+BCS) [8-10] calculations. In the case of Gogny force the HFB theory also predicts both observed features [11,12]. The resulting barriers are generally lowered and the changes depend on the region of deformation and on the nucleus as well.

In the case of HFB self-consistent calculations the symmetry breakup is obtained naturally as a solution of the HFB equations. In the case of macroscopic-microscopic models degrees of freedom responsible for the axial symmetry breakup are introduced ad hoc leading to the increase of the dimension of deformation space. Deformation parameters introduced in this way do not exhaust all possible configurations of the nuclear matter distribution. On the other hand, the HFB theories deliver the optimal configurations of the mean field and the nuclear shape as well.

MODEL and RESULTS

The presented calculations were performed for fermium even-even isotopes with neutron numbers N=136-166 by using the SkM* energy density functional [2] in the particle-hole (ph) channel. In the particle-particle (pp) channel we employed the density-dependent delta interaction (DDDI) in the mixed variant, fitted to experimental pairing gaps of ^{252}Fm.

The calculations were done using the solver HFODD (v. 2.45g) [13] that allows for an arbitrary symmetry breaking. For the basis, we took the lowest 1140 single-particle states of the deformed harmonic oscillator with N_{shell}=26. This corresponds to 17 oscillator shells at the spherical limit.

In this study, only specific static fission paths are considered; they have been obtained in the calculations presented in [14,15]. Specifically, for the fermium isotopes considered, one predicts both reflection-symmetric (s) and reflection-asymmetric (a) fission valleys. There are two kinds of symmetric paths predicted, namely, the valley that corresponds to elongated fission fragments (EF), and that with more compact (CF) fragments that resemble spherical ^{132}Sn clusters when approaching ^{264}Fm. The shorthand notation sEF means symmetric elongated fragments fission path; similarly aEF and sCF correspond to asymmetric elongated and symmetric compact fragments, respectively.

Figure 1 shows the fission barriers in the fermium chain isotopes from A=236 to A=266. The light isotopes of Fm are reflection asymmetric for deformations Q_{20} > 150 b, while the heavier (A≥258) are reflection symmetric. The pre-scission point configurations are shown in Fig. 2.

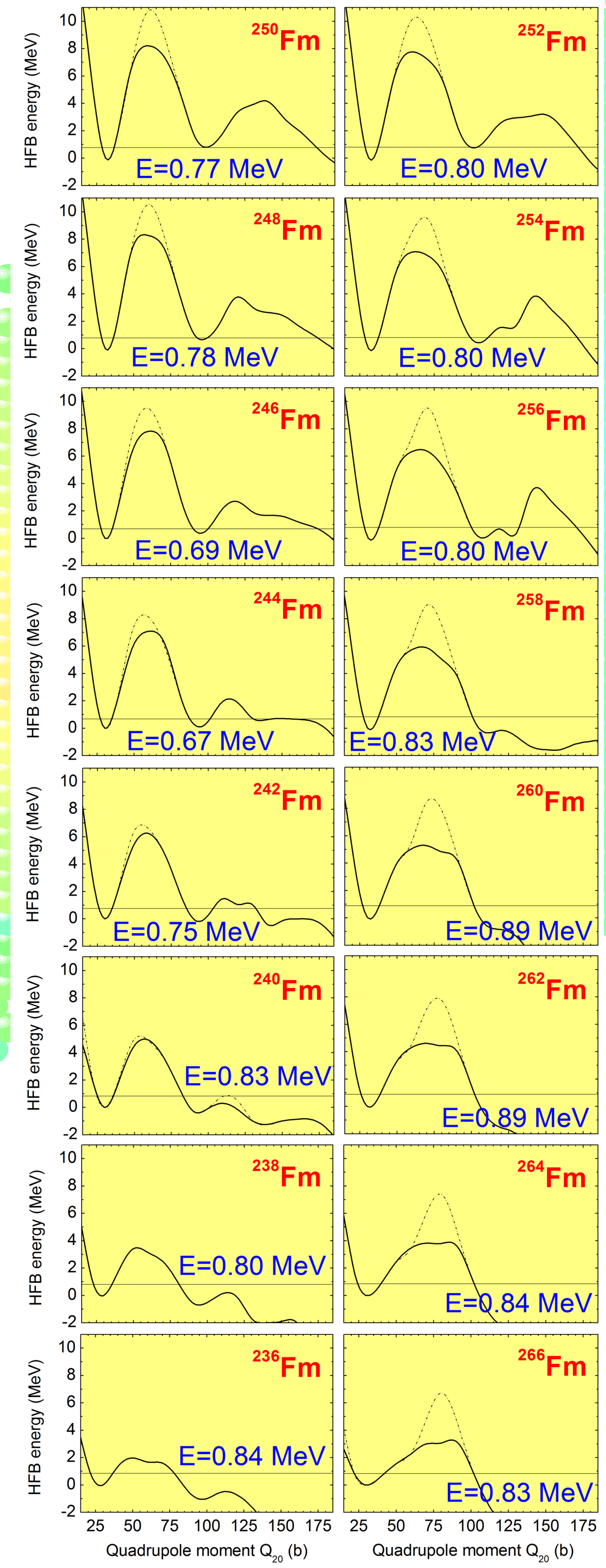

Figure 1: Static fission barriers of fermium even-even isotopes (A=236-266) as calculated in HFB theory with the Skyrme SkM force. The differences between the dash-dot and solid lines in the region of the inner barrier show the energy reduction due to appearance of the triaxial distortions.*

CONCLUSIONS

The HFODD code employed allows for an arbitrary symmetry breaking. This feature is of crucial importance when discussing spontaneous fission where the reflection-asymmetric and triaxial shapes can play a role. The main conclusions of this work can be summarized as follows:

- for *heavy* fermium isotopes (A≥256), the breaking of axial symmetry leads to the decrease of the inner barrier heights of about 3-3.5 MeV,
- in the case of *light* fermium isotopes (A≤240) axial symmetry is preserved,
- for A=236 and A=238 the symmetric elongated fission (sEF) is observed,
- for A=240 to A=256 the asymmetric elongated fission (aEF) is found,
- for A=260 to A=266 the symmetric compact fission (sCF) is found,
- for A=258 the bimodal fission (sEF+sCF), see [15].

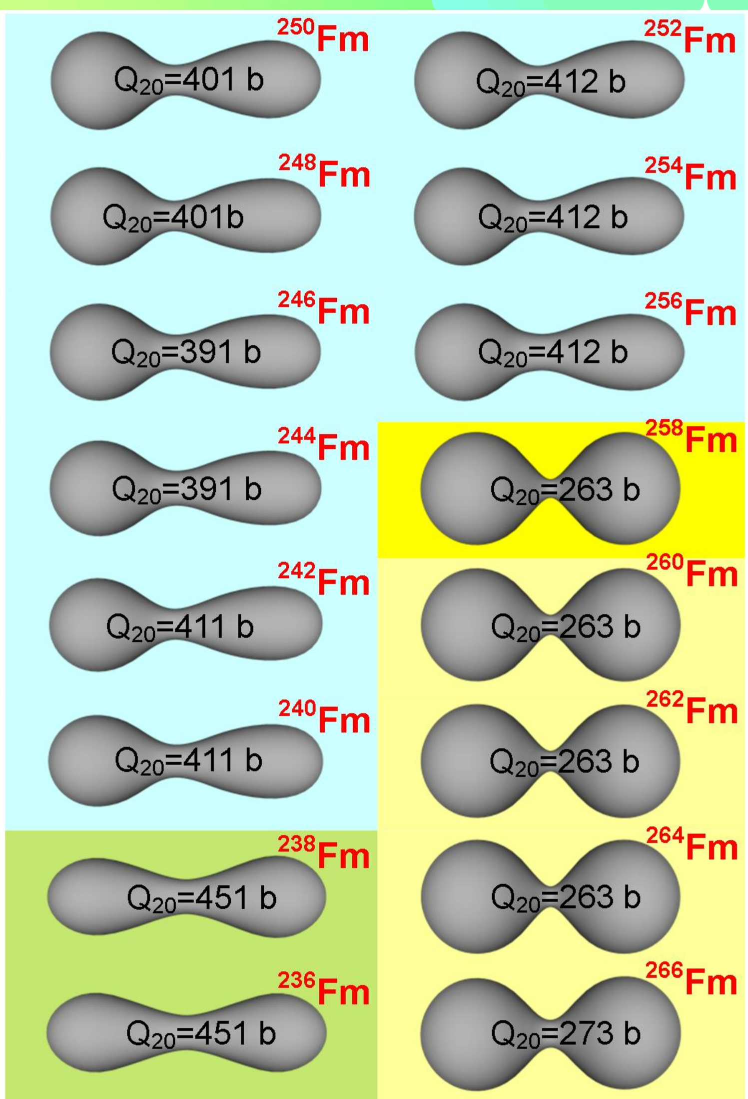

Figure 2: Pre-scission shapes of fermium (A=236-266) isotopes.

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REFERENCES

1. E. K. Hulet *et al.*, Phys. Rev. C **40**, 770 (1989).
2. J. Bartel, P. Quentin, M. Brack, C. Guet, H.B. Håkansson, Nucl. Phys. A **386**, 79 (1982).
3. S. E. Larsson, I. Ragnarsson, S. G. Nilsson, Phys. Lett. **38**B, 269 (1972).
4. S. E. Larsson and G. Leander, in *Physics and Chemistry of Fission 1973*, vol. 1, p. 177. IAEA, Vienna, Austria, 1974.
5. V. V. Pashkevich, Nucl. Phys. A **477**, 1 (1988).
6. S. Ćwiok, A. Sobiczewski, Z. Phys. A **342**, 203 (1992).
7. P. Möller, D. G. Madland, A. J. Sierk, A. Iwamoto, Nature 409, 785 (2001).
8. S. Ćwiok, P.-H. Heenen, W. Nazarewicz, Nature 433, 705 (2005).
9. L. Bonneau, P. Quentin, D. Samsoen, Eur. J. Phys., A **21**, 391 (2004).
10. L. Bonneau, Phys. Rev. C **74**, 014301 (2006).
11. M. Warda, J. L. Egido, L. M. Robledo, K. Pomorski, Phys. Rev. C **66**, 014310 (2002).
12. J.-P. Delaroche, M. Girod, H. Goutte, J. Libert, Nucl. Phys. A **771**, 103 (2006).
13. J. Dobaczewski *et al.*, Comput. Phys. Commun. **180**, 2361 (2009).
14. A. Staszczak, J. Dobaczewski, W. Nazarewicz, Acta Phys. Pol. B**38**, 1589 (2007).
15. A. Staszczak, A. Baran, J. Dobaczewski, W. Nazarewicz, Phys. Rev. C **80**, 014309 (2009).